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Research Department Report

PROVING EXPERIMENTS ON AN ACOUSTIC TRANSMISSION SUITE AND ITS REVERBERATION ROOM

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Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

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Summary

An Acoustic Transmission Suite is a facility used for the laboratory measurement of the airborne sound transmission properties of partitions. It consists of a pair of adjoining rooms, the source room and the receive room, with a hole for the construction of the test partition in their common walls. The building is designed to minimise the sound power flow by paths other than that through the test partition. Such a facility has recently been built at BBC Research Department.

A double brick cavity wall was built to allow the limiting sound insulation performance between the source and receive rooms in the Transmission Suite to be measured. This performance is effectively equal to that which would be measured with a perfectly isolating partition in place, and limits the maximum insulation that could be measured using the Suite. The actual isolation was shown to be impaired by a rigid bond between the test wall and the receive room walls.

A demountable lightweight partition was fitted firstly to the receive and then to the source room side of the test wall. This improved the isolation of the test wall and proved that the rigid bond at its edges had been the cause of the impaired isolation. It also revealed a void above the test wall, and a further weakness through the cavity between the source and receive rooms.

The mean limiting sound reduction index between the source and receive rooms was shown to be 65 dB, provided that the cavity between source and receive rooms was sealed. In future, a mechanism must be employed which provides vibration isolation between the test wall and the Transmission Suite building structure.

The receive room was designed to meet the specifications detailed in the ISO-Standard for reverberation rooms. Proving tests were carried out on the reverberation room and repeatability tests were carried out to evaluate the minimum number of decays needed in each frequency band for absorption coefficient measurements. The amount of additional diffusion needed in the reverberation room to ensure reliable results was determined.

Index terms: *Sound; sound insulation; reverberation; rooms; absorbers*

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PROVING EXPERIMENTS ON AN ACOUSTIC TRANSMISSION SUITE AND ITS REVERBERATION ROOM

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1. INTRODUCTION

1.1 Transmission Suites

Transmission Suites are intended for the measurement of the airborne sound transmission properties of test walls and other building elements. The design features of an ISO-standard Transmission Suite[1] will be explained by describing the new Transmission Suite at Research Department, which was designed principally for the testing of novel lightweight partitions. A plan view of the BBC Research Department Transmission Suite is shown in Fig. 1.

The airborne transmission is measured by using a continuous, wideband acoustic source in the source room. The average sound pressure level (s.p.l.) in both source and receive rooms is measured, usually using a calibrated microphone fitted to the end of a rotating microphone boom to obtain a spatial and temporal average. The difference between the sound pressure levels in the two rooms is a measure of the performance of the test partition.

The source and receive rooms are designed to be structurally and acoustically isolated from each other. This reduces the propagation of sound between the rooms through any path other than that through the wall under test, which is built between them. The source room is a complete 'box' supported on rubber anti-vibration mounts (avms) and is designed to be structurally separate from all other parts of the building. For the receive room, the floor slab is supported on a layer of mineral wool, which acts as an avm, and the walls were built directly onto rubber avms. For stability, the walls of the receive room are tied to the remainder of the building structure using flexible wall ties.

The aperture for the test partition is 3 m high by 4 m wide in the walls between the two rooms. Normally, the test partitions would be constructed on the exposed foundation in the gap between the two rooms. Heavy partitions must be built there because of the load-bearing limitations of the isolated floor slabs.

1.2 Presentation of results

The measured sound level difference, SLD, depends on a number of parameters in addition to the transmission coefficient of the test partition. These are the area of test partition, the reverberation time (in each frequency band) in the receive room and the receive room volume. To make the results depend only on the material and construction of the test wall, they are usually normalised to a sound reduction index[2], SRI (or transmission loss, TL), given by

$$\mathrm{SRI} = \mathrm{SLD} + 10\log_{10}(ST/0.161\,V) \qquad (1)$$

where

S = area of test partition (m^2),
T = reverberation time in the receive room (s),
V = receive room volume (m^3).

An example of the relationship between SLD and SRI in a typical broadcast studio can be calculated from Equation 1. In a television studio of volume 10 000 m^3 with a reverberation time of 0.5 s, the sound level difference for a wall of area 500 m^2

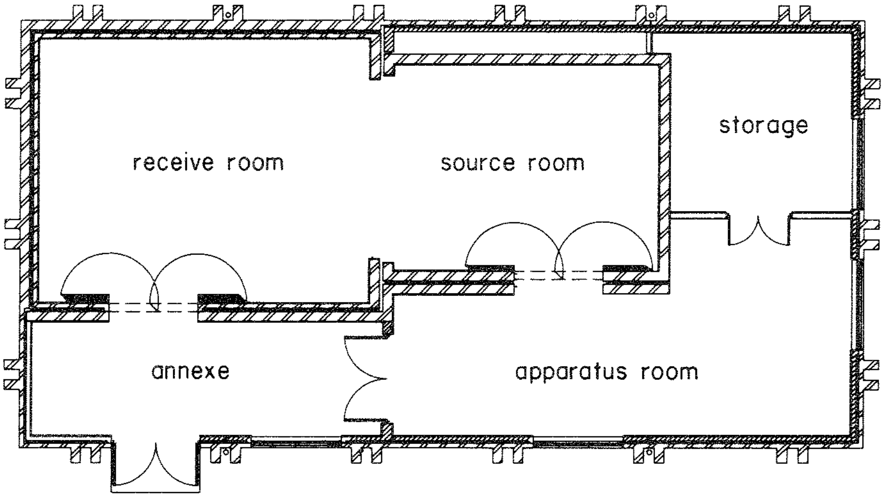


Fig. 1 - A plan of the Transmission Suite.

will be theoretically 8 dB greater than the sound reduction index. As another example, the SLD for a wall of area 30 m^2 in the side of a control room of volume 150 m^3 and a reverberation time (RT) of 0.2 s will be 6 dB greater than the SRI. SRI values will usually be lower than SLD values in studios and so the sound reduction indices should not be compared directly with the sound level difference requirements.

2. THE TEST BRICK WALL

2.1 Concept of the wall

After the completion of the construction of the Transmission Suite, a method was needed to quantify the greatest sound insulation that can be measured in the Suite. In principle, by building a massive test wall in the aperture between the source and receive rooms, the limiting isolation of the Suite could be measured. The test wall was required to perform better than any conceivable partition that might be tested in the future, within the design limitations of the facility. It also had to perform better than the sum of all flanking paths. *Flanking paths* occur between two areas when sound leaks round the side of the wall which divides the areas rather than taking the *direct path* through the wall. A double brick cavity wall was proposed for the proving experiments. Blockwork was not used in the test wall as it was argued that it might 'ring'[3a] (that is, resonate).

2.2 Design and construction of the wall

Fig. 2 shows a cross-section of the cavity brick wall built into the opening between the source and receive rooms (the lightweight partition used in later experiments is also shown). The brickwork consisted of two leaves of 103 mm sand lime bricks (density 2,030 kg/m^3) with a 50 mm cavity. The brick 'frogs' were laid upwards to ensure that they were fully filled with mortar to prevent air pockets. The bricks were built up to the surface of the reveal of the test aperture, and mortar was rammed in above the top course of bricks to try to achieve a good acoustic seal.

To minimise the acoustic coupling, no wall ties were used (for acoustic reasons) in the wall cavity which was filled with glass fibre insulation to reduce the potential for debris causing an acoustic bridge. The glass fibre would also help to improve the middle and high frequency insulation by damping natural oscillations of the wall[4a] and by absorbing sound in the cavity.

A two-coat gypsum plaster was used to provide a smooth finish, and to seal up the bricks and mortar to prevent sound leakage through cracks, voids or the porous bricks and mortar. The undercoat was Browning and the top coat was Finish plaster. The wall was plastered on the receive room side only, as plastering both sides would only have given a marginal improvement in isolation[5a]. The plaster was painted with two coats of eggshell emulsion as a final seal.

2.3 Measurements made while constructing the wall

Fig. 3 shows the sound reduction indices for the wall in various stages of completion. The mean value shown in the figure is the average SRI over the frequency range 100 Hz to 2.5 kHz. Adding the plaster increased the high frequency isolation by more than would be expected from the mass increase. This is a well-known phenomenon which occurs because the plaster surface stiffens up the wall and also seals up any leaks in the surface. The isolation decreased as the plaster and mortar dried out, because the water provides extra mass and seals up the porous plaster, brick and mortar[5b]. Thus any test wall should be allowed at least five days to dry out before its final performance is measured.

2.4 Comparison of the performance of the test wall with that of other cavity brick walls

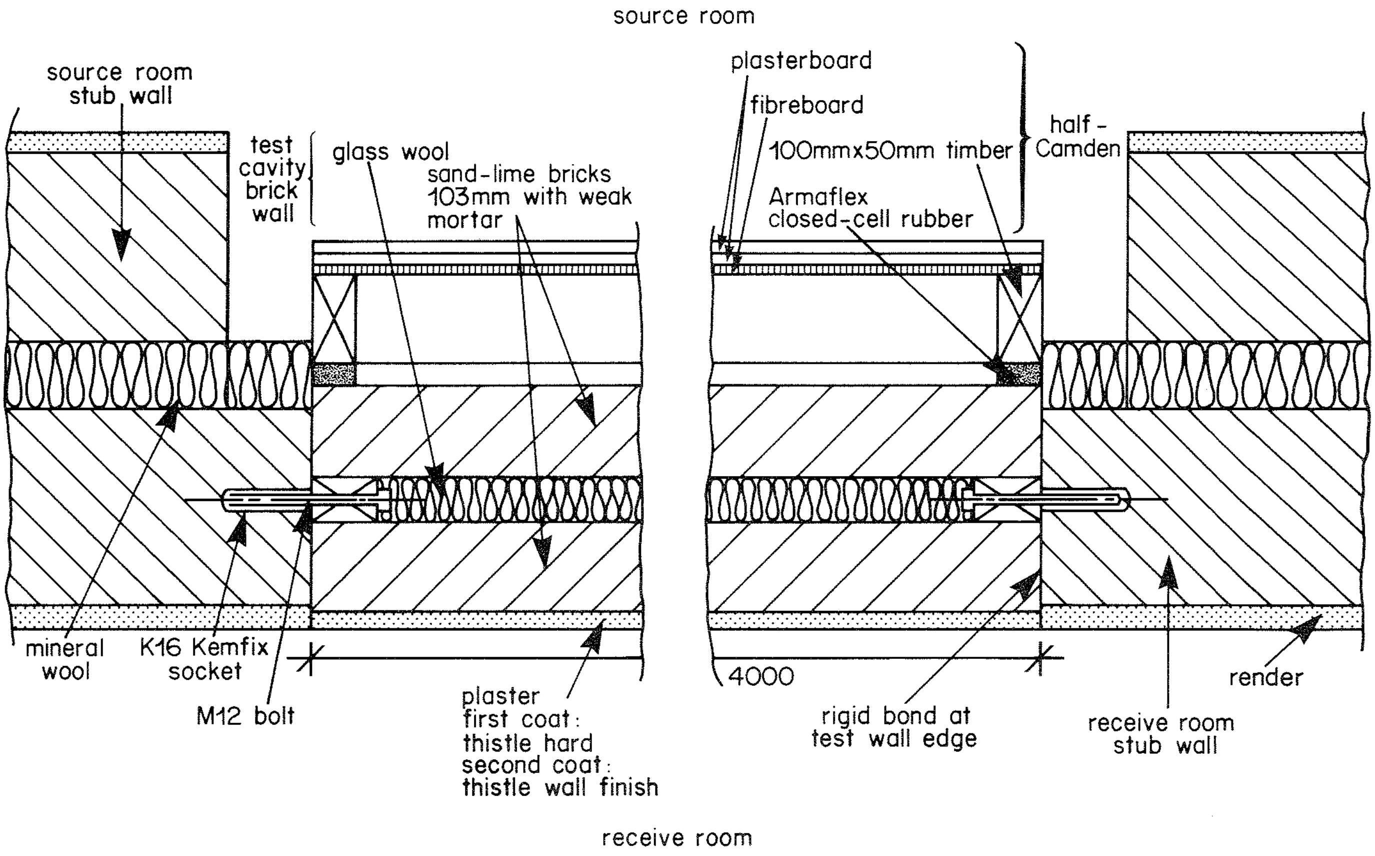
Fig. 4 shows the performance of the test wall compared with the mean of five field results for walls of similar design derived from a BBC Sound Insulation Database[6]. In this case, because the common partition areas and receive room dimensions were not known for the field data, the standardised sound level differences have been calculated, rather than the sound reduction indices. Results are expressed in terms of a sound pressure level difference corrected to a reverberation time of 0.5 s in the receive rooms. The standardised SLD is given by[7]

$$\mathrm{SLD}_{0.5s} = \mathrm{SLD}_{\mathrm{measured}} + 10 \log_{10}(T_1/T_2) \quad (2)$$

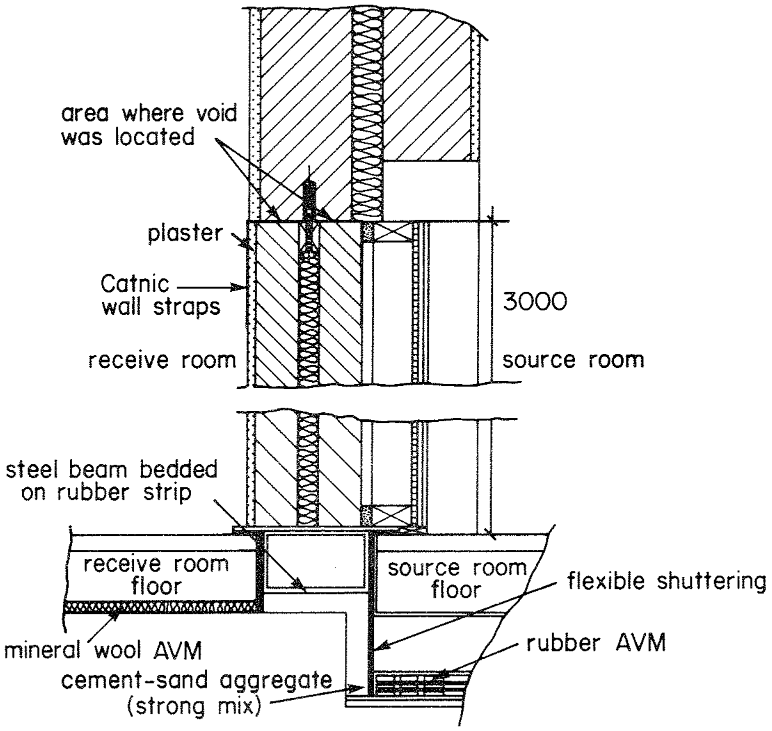
where

T_1 = actual RT in the receive room,
T_2 = 0.5 s (the reference reverberation time).

The test wall results are better than the field measurements below 400 Hz and above 2 kHz. The mean SLDs (between 100 Hz and 2.5 kHz) are again very similar in both cases, although the test wall has a lower isolation than the field results between 400 Hz and 2 kHz (by as much as 6 dB at 500 Hz). In this case the mean field results show a similar, but narrower, dip at around 315-400 Hz.



horizontal section (plan view)



vertical section (elevation)

Fig. 2 - Cross sections through the test wall showing the half-Camden in position.

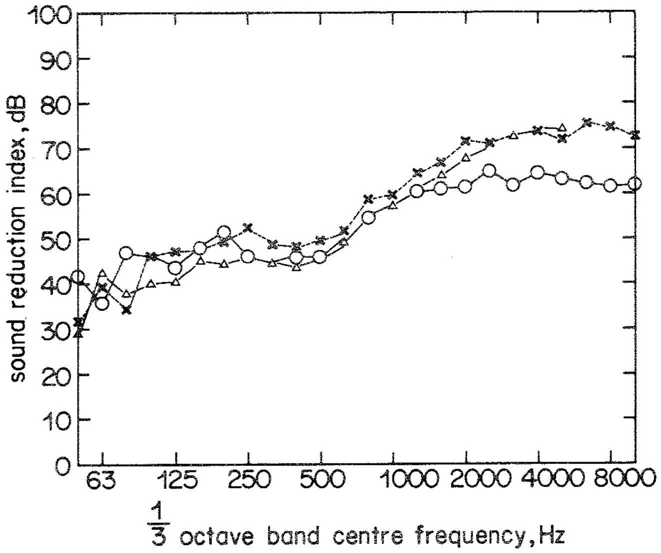


Fig. 3 - Performance of the test wall during construction.

(Mean values shown in brackets)

○——○ (a) (52.1) two leaves, no plaster
×- - - -× (b) (55.7) two leaves, with plaster before drying-out period
△——△ (c) (51.8) two leaves, with plaster after drying-out period

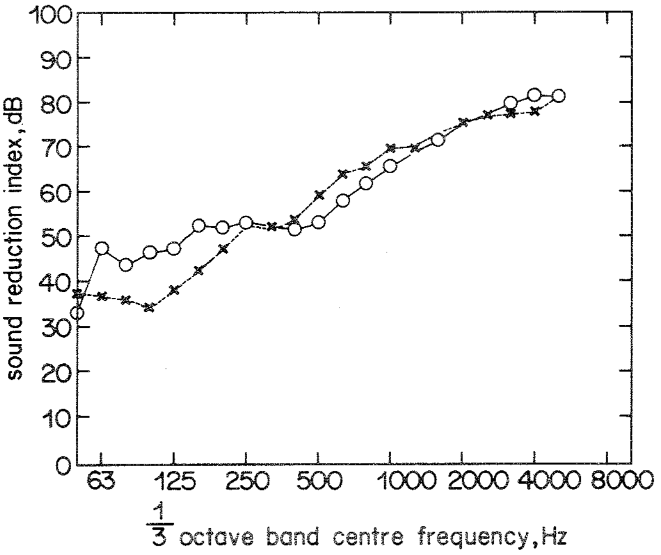


Fig. 4 - Initial measurements of the performance of the test partition.

All values are corrected to a reverberation time of 0.5 s in the receive room.

(Mean values shown in brackets)

○——○ (a) (59.0) test wall
×- - - -× (b) (58.2) average for five walls of similar design (Ref. 6)

Fig. 5 compares the SRI of the test wall with that for cavity brick walls from a number of other sources[8a,4b,9]. The test wall performed much better than the others below 315 Hz and performed better than the results from Beranek and Gilford above 1.6 kHz. Between 315 Hz and 1.6 kHz, the calculated SRI for the test wall levels off and is 5 dB lower than the worst of the other walls at 500 Hz. However, the mean SRIs between 100 Hz and 2.5 kHz agree closely in all cases. All the above results show that the performance of the test wall was lower than expected, and insufficient to quantify the limiting sound insulation performance of the Transmission Suite.

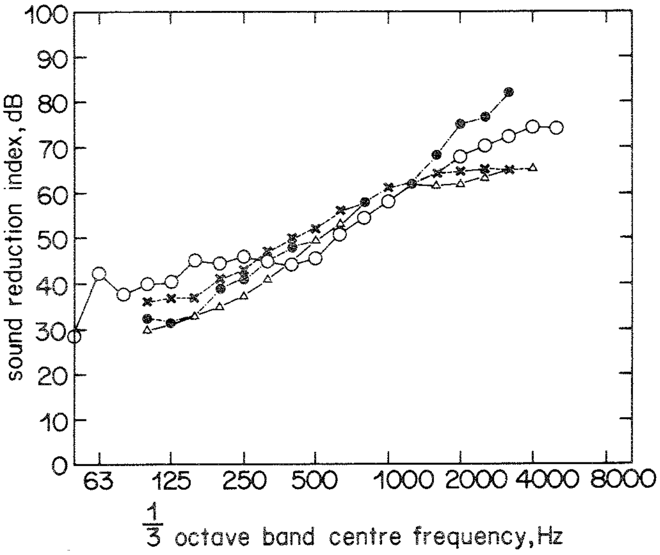


Fig. 5 - Comparison of the performance of the test partition with the performance of others having a similar construction.

(Mean values shown in brackets)

○——○ (a) (51.8) test partition
×- - - -× (b) (51.6) example in Ref. 8 from BRE
△——△ (c) (48.0) example in Ref. 4b
●—·—● (d) (51.6) example in Transmission Loss Database (Ref. 9)

Curve (b) is for a 113-50-113 mm cavity brick wall plastered on both sides: it is the mean of a number of field results supplied by the Building Research Establishment.

Curve (c) is for a typical cavity brick wall.

Curve (d) is the mean of a number of cavity brick walls measured in a Transmission Suite by the NPL.

Fig. 6 shows the SRI of the test wall compared with a field result for a cavity wall with a bridged cavity[8b]. The bridge was caused by a solid concrete foundation on which both leaves of the wall stood. In this case the shapes of the SRI curves for the test wall and the field result are very similar, although the field result has a slightly higher SRI in most frequency bands. Both show dips at around 400-500 Hz. It could be that the bridge at the edges of the wall, where it was in contact with the receive room walls, both improved the low frequency performance and caused a dip at about 400 Hz.

The mean of two Transmission Suite results for a 225 mm brick wall[9] is also shown, in Fig. 6(c). The SRI of the test wall is close to that of the 225 mm brick wall around 400 Hz, but it is slightly higher at other frequencies. However, the results for the test

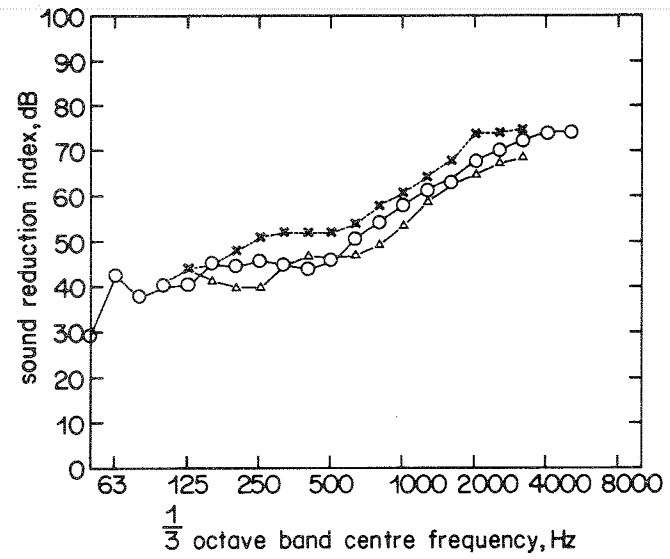


Fig. 6 - Comparison of the performance of the test partition with the performance of others having a related construction.

(Mean values shown in brackets)

o———o (a) (51.8) test partition

x- - - - -x (b) (55.9) example in Ref. 8 from Norwegian Hospital

△———△ (c) (49.2) example in Transmission Loss Database (Ref. 9) for 225 mm Brick Wall

wall and the 225 mm brick wall are not significantly different, and it appears that the bridge may have been making the cavity in the test wall ineffective, especially at around 400 Hz.

2.5 Attempts to locate flanking paths

2.5.1 Effects of pugging

It was thought that the cavity between the source and receive room stub walls might constitute an airborne flanking path. To test this hypothesis, sand (pugging) bags were packed into the cavity so that they filled its full width. Fig. 7 shows how the SRI of the wall varied with the amount of pugging. Pugging slightly improved the SRI above 1.6 kHz. The differences between the curves at higher frequencies are statistically significant, but not large, which implies that airborne flanking paths through the cavity are only marginally important. However, the low frequency differences can be accounted for solely in terms of statistical uncertainty[10].

2.5.2 Vibration measurements — measurement of flanking transmission with accelerometers

Using accelerometers to measure vibration, it was shown that the receive room walls were vibrating when the source room was driven with a wideband acoustic source. There were two possible causes of this vibration:

a) Sound power was flowing into the receive room from the cavity surrounding it, or by some form of mechanical coupling, and therefore the receive room walls were being driven from outside.

b) The sound field in the receive room caused by transmission through the test wall was driving the walls from the inside of the receive room.

Case a) would be a flanking path, and so the cause of the vibration had to be found.

To find the cause of this vibration, loudspeakers in either the source or receive rooms were driven with a wideband source. The vibration levels at a number of points on the receive room walls were measured with an accelerometer. Fig. 8 shows the difference between the vibrations in the receive room walls for either the wideband acoustic source in the source or receive rooms (corrected to the same s.p.l. in the receive room). Because the receive room walls vibrated relatively much more when the sound source was in the source room, case a) is true, i.e. sound power was flowing into the receive room via its walls.

Calculations showed that a significant amount of power was flowing into the receive room via these walls, compared with the power flow through the test wall. This constitutes a flanking path, which reduced the measured SRI of the test wall. The cause of the driving force from outside on these walls had to be found.

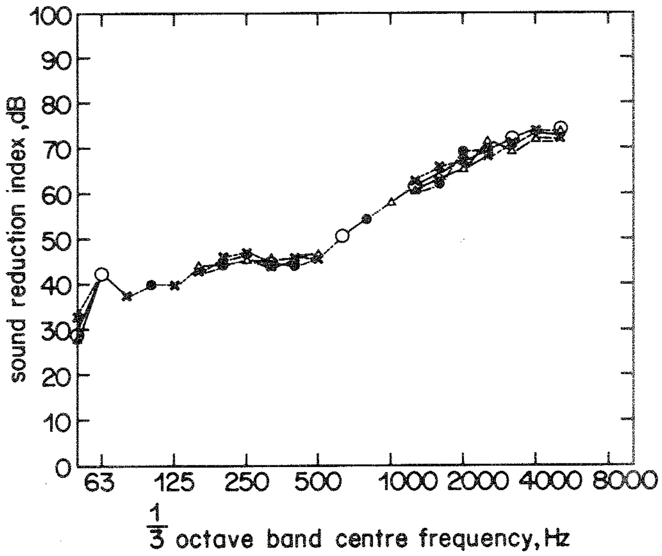


Fig. 7 - The effect of pugging the cavity between the source and receive rooms on the SRI of the test wall.

o———o (a) fully pugged

x- - - - -x (b) pugged except for left side

△———△ (c) only top pugged

●-·-·-·-● (d) no pugging

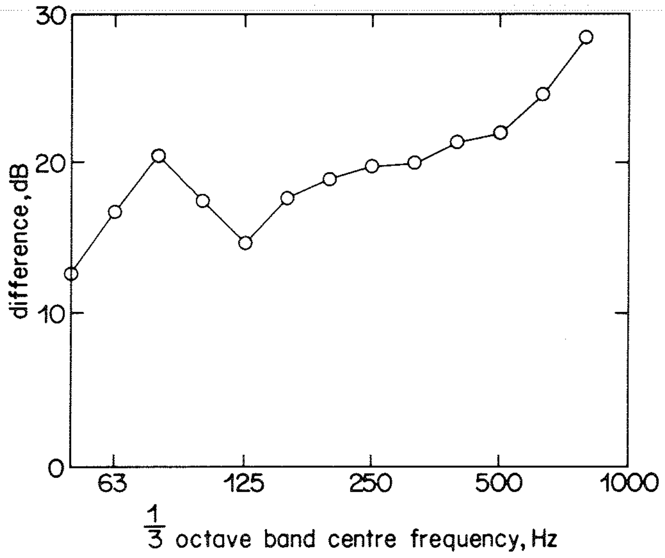


Fig. 8 - (Vibration in the receive room walls for a source in the source room)/(vibration in the receive room walls for a source in the receive room) ... for the same s.p.l. in the receive room in both cases.

A vibration path was proposed which would explain this acoustic power flow. For structural and acoustic sealing reasons, the test wall had been rigidly bonded with mortar to the receive room walls at its sides and top. Thus, when sound waves in the source room caused the test wall to vibrate and thus transmit sound, the receive room walls also would be forced to vibrate and radiate sound into the room because of this rigid bond.

To test this hypothesis, two alternative sources were used. The first source was a wideband, airborne acoustic signal produced in the source room by a loudspeaker. The second was sledgehammer impacts on the source room leaf of the test wall. In both cases, the vibration of the receive room walls and the vibration of the receive room leaf of the test wall were compared using the average of several accelerometer positions.

Fig. 9 shows the difference in decibels (or ratio) between the average vibration of the test wall and that of the receive room walls in ⅓rd octave form. The results for the wideband acoustic source and hammer blows agree closely. Hitting the test wall on the source room side will cause the receive room walls to vibrate because of the rigid bond between them, via the bridge around the perimeter. As the two curves in Fig. 9 agree closely, it is probable that the same mechanism applies for coupling the source room s.p.l. to receive room wall vibration in both cases.

This tends to support the hypothesis that the rigid bond at the test wall edges provided a flanking path and reduced the apparent SRI of the wall. It should be noted that the air in the cavity between the two leaves of the test wall was a coupling element. However, the isolation provided by the air in the cavity at around 400 Hz would have been much higher than the isolation through the rigid bond at the test wall edges.

2.5.3 Mechanical coupling between various room surfaces

An investigation was required to find whether any parts of the source room were mechanically coupled to any parts of the receive room with the test wall in place. This was achieved by hitting various source room surfaces with a sledgehammer, and measuring the transfer function of vibration between a point on the room surface close to the hammer impact and a point on the receive room surface using accelerometers and an FFT analyser in its impulse mode.

Fig. 10 shows the transfer functions in ⅓rd octave form for 16 combinations of source and receive room accelerometer positions. The source room ceiling, walls and floor had levels of isolation from the receive room between about 30 and 50 dB indicating that there were no significant structural bridges at these locations. The isolation between the source and receive room sides of the test wall was very small because the two leaves were bridged at the edges of the test wall. The isolations between the source room side of the test wall and either the floor, walls or ceiling of the receive room are all lower than the isolations from other surfaces in the source room.

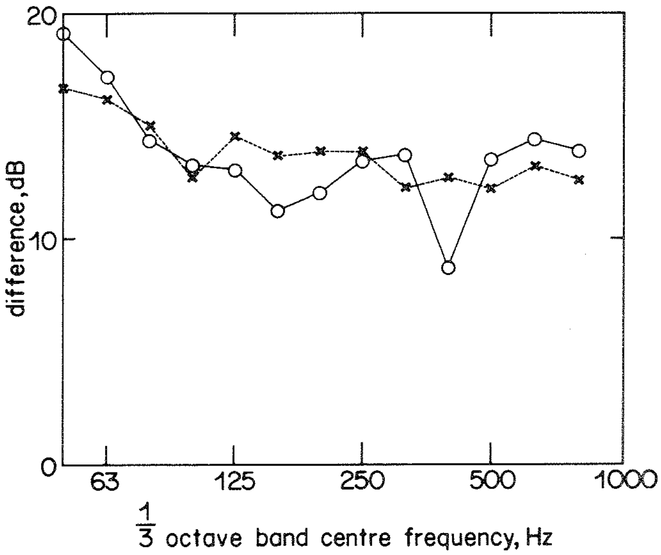
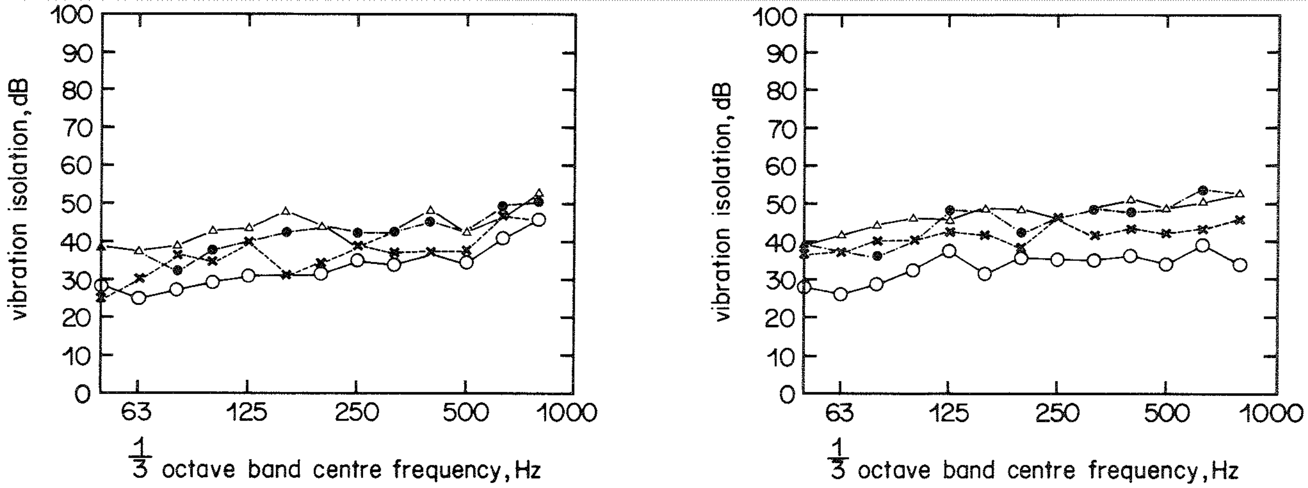


Fig. 9 - Difference between the vibration of the receive room side of the test partition and the vibration of the receive room walls.

o———o hammer on source room side of the partition

×- - - - -× white noise in the source room

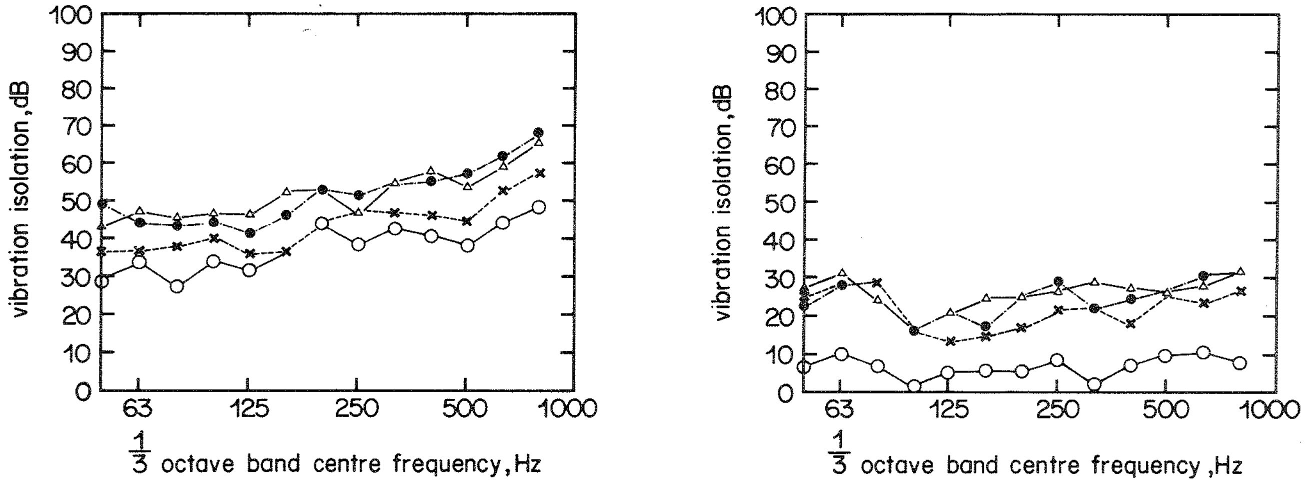


(a) Vibration isolation between the source room ceiling and:

○——○ the receive room side of the test wall
×- - - -× the receive room walls
△——△ the receive room floor
●——● the receive room ceiling

(b) Vibration isolation between the source room floor and:

○——○ the receive room side of the test wall
×- - - -× the receive room walls
△——△ the receive room floor
●-·-·-● the receive room ceiling



(c) Vibration isolation between the source room walls and:

○——○ the receive room side of the test wall
×- - - -× the receive room walls
△——△ the receive room floor
●——● the receive room ceiling

(d) Vibration isolation between the source room side of the test wall and:

○——○ the receive room side of the test wall
×- - - -× the receive room walls
△——△ the receive room floor
●-·-·-● the receive room ceiling

Fig. 10 - Vibration isolations between source room surfaces and receive room surfaces.

To conclude, no parts of the source room were closely coupled to the receive room. However, the rigid bond at the edges of the test wall strongly coupled the test wall to the receive room walls.

2.6 Wave coincidence

Another possible cause of the dip in the SRI of the test wall around 400 Hz was *wave coincidence*^{4c}. Wave coincidence can occur when a sound wave strikes a wall at an oblique angle. At a certain frequency, the wavelength of the airborne sound wave in the plane of the wall (which is proportional to the sine of the incidence angle) will become equal to the natural bending wavelength of the wall at that frequency. Resonance will occur resulting in a dip in the SRI curve. At normal incidence, this resonance frequency will be infinite. As the angle of incidence moves towards 90°, this coincidence frequency will diminish to approach a *critical frequency*, which is the lowest frequency at which wave coincidence can occur.

In a reverberant field, the SRI of a partition will theoretically be given by the envelope of the minimum of all curves for all incidence angles. The depth of the dip will be reduced by damping in the wall. For a single 100 mm brick wall, the critical frequency will be approximately 290 Hz[4d]. For identical leaves, wave coincidence will occur at the same frequency in each leaf, and so a dip starting at 290 Hz would be expected. This frequency is lower than that of the observed frequency of the dip for the test wall, and there are two possible reasons for this:

a) The 290 Hz estimate of the critical frequency is only an approximate value for a typical brick wall. The critical frequency will vary with the type of brick and the type of mortar used.

b) The assumption that wave coincidence was responsible for the dip in the SRI curve may be incorrect.

It was necessary to carry out further developments on the test wall in order to resolve this uncertainty.

3. IMPROVEMENTS TO THE TEST WALL — ADDITION OF A HALF-CAMDEN

3.1 Concept of the half-Camden

Two problems arose as a result of the tests on the double brick cavity wall. First there was a dip, centred on 400 Hz, in the SRI curve for the wall which might have been caused either by wave coincidence or by the rigid bond of the cavity at the test wall edges. Second, the rigid bond between the test partition and the receive room walls appeared to be reducing the overall isolation by coupling vibrations directly into the receive room walls. Both problems would explain the poor acoustic performance of the test wall, which did not have an isolation sufficient to allow measurement of the flanking leakage in the Transmission Suite.

A method was proposed to study further the nature and magnitude of both problems. A demountable half-Camden (a type of lightweight partition) would be constructed which could be mounted on either the source room or the receive room side of the test wall on flexible supports. The intention was that the different effects of putting the half-Camden alternately on the source and receive room sides of the test wall could be used to differentiate between the possible reasons for the poor performance. The resulting improved isolation would allow other air- or structure-borne flanking paths to be detected.

By having a different mass and construction, the coincidence effects of the half-Camden would be different from those of the brick wall and so there would be a significant improvement in the isolation in the 400 Hz region. The improvement would be independent of which side of the test wall the half-Camden was mounted. If, however, the weakness was mainly caused by bridging of the cavity in the test wall, then the effects of adding the half-Camden would be much smaller, mostly as a consequence of the slight increase in the overall mass of the wall and the stiffness of the air entrapped. This effect would also be independent of which side of the test wall the half-Camden was mounted.

In assessing the significance of the bond between the test wall and the receive room walls, the vibration in the receive room walls would only be reduced when the half-Camden was mounted on the source room side of the test wall. This is because the flexible supports of the half-Camden can only reduce vibration when they are in between the sound source and the exposed test wall surface in the source room.

3.2 Design and construction of the half-Camden

The design of the half-Camden was based on recommendations in the BBC Guide to Acoustic Practice[3b]. It consisted of two layers of 12.5 mm thick plasterboard and one layer of 12.5 mm thick fibreboard nailed to one side of a 100 mm thick planed timber framework. The plasterboard and the air it entraps act as a mass-spring resonance with a natural frequency[11] given by

$$f_0 = 1900/\sqrt{(dm)} \qquad (3)$$

where

m = mass of the plasterboard (kg/m^2),
d = cavity width (mm).

The cavity width was made large, and two sheets of plasterboard were used to increase the mass to keep the fundamental resonance frequency low (33.7 Hz). The fibreboard is absorbent and damps the plasterboard sheet, so no additional cavity damping was used.

The half-Camden was isolated from the test wall and floor with closed-cell foam rubber insulation sheet. Scale model tests were performed to measure the resonance frequency of blocks of concrete standing on the rubber sheet and they showed that the vertical resonance frequency of the half-Camden would be less than 20 Hz. Isolation from the floor above this frequency should be sufficiently large to prevent mechanical coupling between the floor and the half-Camden. The stiffness of the rubber seals between the wood frame and the brick wall was small compared with the stiffness of the entrapped air.

3.3 Remedial work before the effects of the half-Camden could be assessed

A defect in the test wall became apparent after initial experiments using the half-Camden. The defect had to be investigated and rectified before the true effects of the half-Camden could be assessed. A thin shrinkage crack (approximately 0.25 mm wide) had appeared at the plaster/render join on the receive room side at the boundary of the test wall after moving the half-Camden from the receive to source room sides of the wall. The crack had probably been encouraged by the changes in wall loading caused when mounting the half-Camden.

Sound leakage through the crack was estimated using a wideband continuous acoustic source in the source room and by listening close to the walls in the receive room and its cracks. Sound leakage at the vertical cracks at the sides of the wall was undetectable. However the leakage from the horizontal crack at the top of the test wall was very pronounced.

The addition of the half-Camden reduced the sound power transmitted through the test wall, which previously had been masking the sound leakage through the crack. It is also possible that the crack opened and closed as the air temperature and humidity changed, and as the test wall and receive room walls dried out and settled on their supports. Some changes in SRI of the bare double brick cavity wall over a period of time support that possibility.

Chipping some of the mortar out near the crack revealed that the mortar on the top course of bricks for each leaf of the test wall extended only 1 cm inwards, and there was a large void above most of the width of the wall. This defect was present despite the fact that the bricklayer had been supervised during the construction. The frogs on the bricks for the top course had been filled with mortar before they were pushed into place, and yet the large void had still occurred.

To fill the void, the remaining mortar and plaster above the top brick course was chipped out. Fresh mortar was rammed in until the void was fully filled. When dry, the exposed surface was coated with mastic to act as a non-porous seal and to allow for shrinkage.

The effect of the repairs was then checked. By listening in the receive room it was noticed that all signs of leakage through the join had been removed. The measured SRI before and after crack repairs is shown in Fig. 11. It is surprising to note that the increase in SRI is so large for such a very thin crack, and that it extends down to 250 Hz.

3.4 Effects of the half-Camden on the overall insulation of the test partition

The sound reduction index of the test wall is shown in Fig. 12 for the half-Camden fitted to either the source or receive room sides of the test wall. Fitting the half-Camden to the receive room side of the wall (Fig. 12(b)) improved the average SRI by only 1.8 dB, and essentially independently of frequency. The small change in the depth of the dip at 400 Hz suggests that the dip was caused more by the bridging of the cavity at its wall edges than by wave coincidence.

Fitting the half-Camden to the source room side of the wall (Fig. 12(c)) increased the isolation much more, having the greatest effect between 315 Hz and 1.6 kHz. This improvement was caused by the reduction of vibration in the test wall and the consequent reduction of vibration transmitted to the receive room walls at the test wall edges.

3.5 Effects of pugging the cavity on the SRI with the half-Camden in place

At this stage in the investigation, the isolation of the partition was considerably higher than that

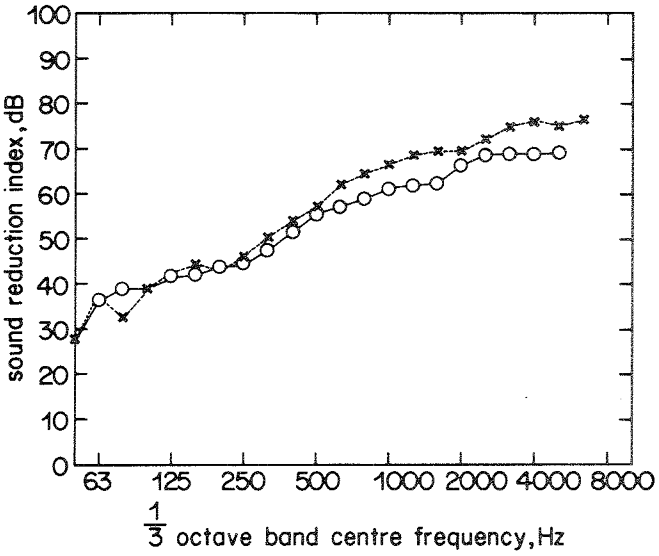


Fig. 11 - The effect of crack repairs on the performance of the test partition.

Half-Camden on source side of brick wall, no pugging in the cavity between the source and receive rooms.

(mean values shown in brackets)

○——○ (a) (53.6) before crack repairs
×-----× (b) (56.7) after crack repairs

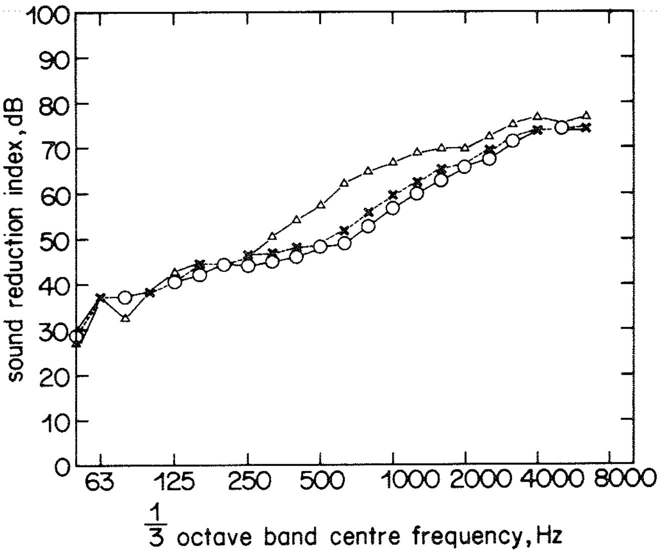


Fig. 12 - The effect of the location of the half-Camden on the performance of the test partition.

After crack repairs, no pugging in the cavity between the source and receive rooms.

(mean values shown in brackets)

O———O (a) (50.8) no half-Camden
×--------× (b) (52.6) half-Camden on receive room side of brick wall
△———△ (c) (56.7) half-Camden on source room side of brick wall

which had been measured for the bare double brick cavity wall. It was therefore decided to remeasure the airborne isolations between the source and the receive room with pugging bags packed into the cavity between the source and receive room stub walls to investigate whether this flanking path could now be quantified. The resulting increase in isolation was large and relatively independent of frequency, as shown in Fig. 13. As a result of this investigation, permanent flexible seals were designed and fitted to block the entrance to the wall cavity in the test aperture reveal.

3.6 Airborne flanking paths through rooms in the Suite

The airborne flanking paths through other rooms in the Transmission Suite had to be quantified. Provided that the sum of the acoustic power flow through all paths other than through the test wall is much less than the power flow through the test wall, flanking paths will be insignificant. If the sound level differences between any two adjacent areas is known, the power flow through any chain of rooms as a single flanking path can be calculated. The total flanking energy is then the sum of all the power flows for each possible flanking path.

Provided flanking paths are insignificant, the isolation of any wall is equal to the sound level difference between the two areas it divides, and so the SLDs were measured between all areas in the suite. From these SLDs, an estimate of the total flanking energy for all paths through either two, three or four walls was calculated.

Fig. 14 shows a comparison between the measured isolation between the source and receive rooms and the calculated worst-case airborne flanking sum. The measurements were made with the half-Camden on the source room side of the test wall (crack repaired), and with the cavity between the source and receive rooms pugged. The flanking isolation through other rooms in the Suite was greater, by between 16 and 55 dB, than that of the test wall under these conditions, and so was considered to be unimportant.

3.7 Evaluation of the results

To summarise, the original test wall had insufficient isolation to allow measurement of the limiting flanking isolation of the Transmission Suite. The performance of the wall was especially poor at around 400 Hz, partly because of wave coincidence but mostly because of the rigid bond at the boundary of the test wall.

As a result of the half-Camden tests, a crack had been located at the boundary at the top of the test wall. When this had been repaired, the flanking isolation was shown to be controlled by the amount of

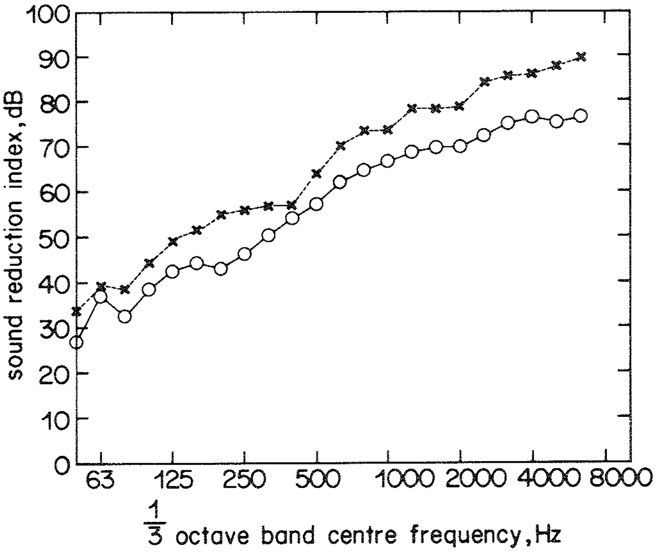


Fig. 13 - The effect of pugging in the cavity between the source and receive room on the measured performance of the test partition.

Half-Camden on source room side of brick wall, after crack repairs.

(mean values shown in brackets)

O———O (a) (56.7) no pugging
×--------× (b) (64.8) with pugging

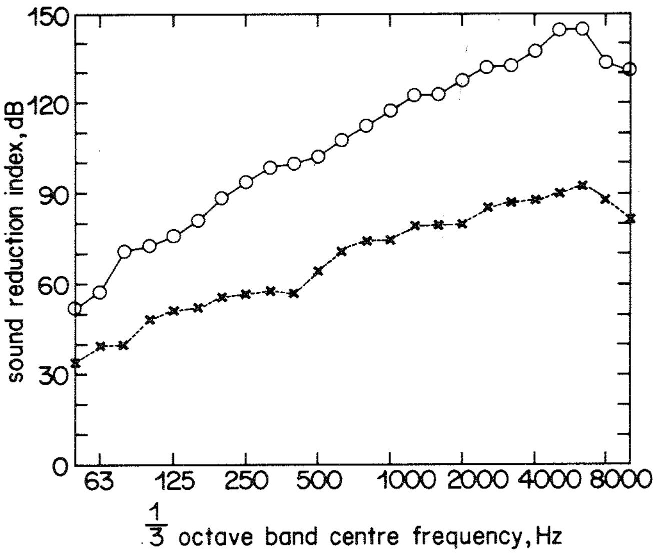


Fig. 14 - Isolations between the source and receive rooms with a pugged cavity and the half-Camden on the source room side of the test partition.

○——○ (a) calculated airborne flanking sum
×-------× (b) measured

sound power flowing via the cavity between the source and receive rooms rather than by airborne flanking paths through other rooms in the Suite.

The best mean sound reduction index observed was just less than 65 dB. As explained in Section 1.2, this would give an average sound level difference in a studio of around 71-73 dB. The Transmission Suite can therefore be used to test walls of mean sound reduction index less than 65 dB if the test wall is built into the opening in the receive room walls. The Suite was designed for the measurement of the sound transmission properties of lightweight metal or timber-framed partitions. The mean sound reduction index of single-leaf, framed partitions generally never exceeds 55 dB, so the Transmission Suite has met its design target. By building some leaves of a multiple leaf wall into the opening in the source room, the highest SRI that could be measured would be increased, but this was not quantified in these tests.

4. ASPECTS OF MEASUREMENT TECHNIQUE

4.1 Effects of reverberation time on measured SRI

SRI should, theoretically, not depend upon the reverberation time in either the source or receive rooms. However, the British Standard method for measurement of SRI in laboratories[1] states that the reverberation time (RT) in any frequency band should not exceed two seconds in both test rooms. Because the RT in the empty source and receive rooms is much greater than two seconds, the effect of RT on the measured SRI had to be investigated.

Fig. 15 shows the effect of source room acoustic treatment on the measure of SRI and Fig. 16 shows the corresponding effects of receive room treatment. Results have been expressed as a difference between the measured SRI for a given level of

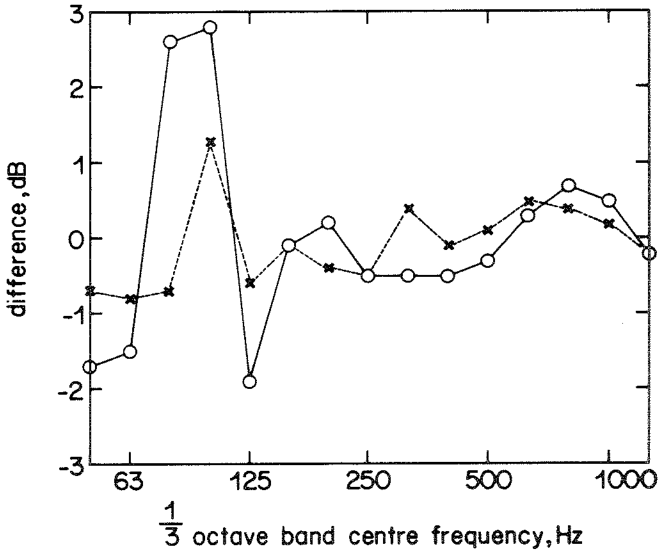


Fig. 15 - Differences between the SRIs of the partition for a treated and an untreated source room.

○——○ receive room untreated
×-------× receive room fully treated

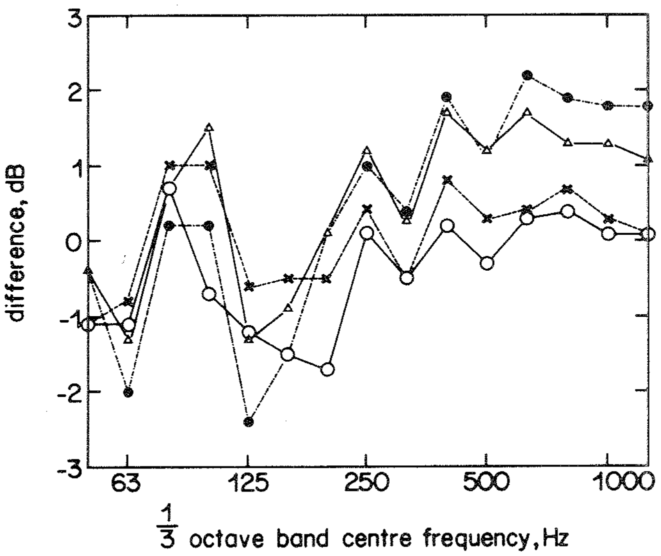


Fig. 16 - Difference between the SRIs of the partition with various numbers of modular absorbers in the receive room and the SRI with an untreated receive room.

(source room untreated)

○——○ 12 modular absorbers
×-------× 24 modular absorbers
△——△ 46 modular absorbers
●-------● 78 modular absorbers

acoustic treatment in the room and the SRI measured with the room empty (to magnify the small changes). When considering the effect of source room acoustic treatment, the SRI was calculated for both a fully treated and an empty receive room. When considering the effect of receive room acoustic treatment, the source room was empty. The rooms were treated with wideband modular absorbers[12].

The source room acoustic treatment had only a small effect on the measured SRI of the wall (Fig. 15). The low frequency differences can be accounted for as statistical variations which increase as the wavelength of the sound increases[10]. The receive room acoustic treatment had a slight effect on the measured SRI (Fig. 16), as shown by the trend in the curves. It might be that these changes were caused by a change in the sound diffusivity in the rooms, and the diffusivity would be affected by the presence of the absorbers. Although these differences were small, they could be measured, and to comply with the British Standard, all SRIs must be measured using sufficient acoustic treatment in both rooms to keep the reverberation times in all frequency bands less than two seconds.

4.2 Effects of diffusivity on measured SRI

As part of other tests, the effect of diffusing elements on the measured absorption coefficient had been studied when assessing the receive room as an ISO-standard reverberation room (see below). The effect of these diffusers in the receive room on the measured SRI of the test wall was also observed with both rooms fully treated with modular absorbers. The results are shown in Fig. 17. Although the measured SLD changed by a small amount, the calculated SRI changed more because of the reduction of RT in the receive room which was caused by the increase in the diffusivity of the sound field. For reliable results, diffusers should be used (as recommended in BS2750) to ensure that the sound fields are as diffuse as possible.

4.3 Repeatability of SRI measurements

The repeatability of calculated SRI values for a wall must be known. To evaluate this repeatability, the random error in both the SLD and the receive room RT must be estimated. From Equation 1 the uncertainty in measured SRI can be calculated from

$$\sigma_{SRI}^2 = \sigma_{SLD}^2 + [(10\log_{10}e)/T]^2\sigma_T^2 \qquad (4)$$

where

σ_{SRI}^2 = variance of the SRI,
σ_{SLD}^2 = variance of the SLD,
σ_T^2 = variance of the receive room reverberation time T.

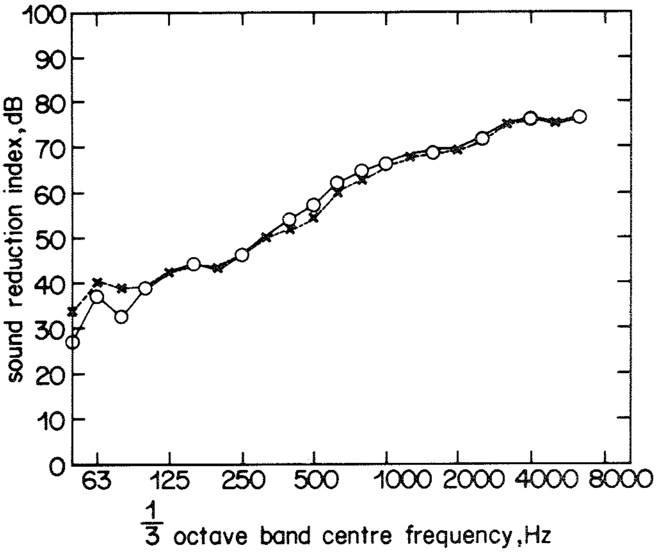


Fig. 17 - The effect of the presence of diffusers in the receive room on the measured performance of the test partition.

(mean values shown in brackets)

o——o (a) (56.7) no diffusers
x------x (b) (55.9) with twelve diffusers

The SLD for the test wall was measured five times over a short period of time, each time for a period of one minute. An estimate of the standard deviation σ_{SLD} was calculated for each ⅓rd octave frequency band. Also, the receive room reverberation time was measured ten times, each time using ten decays in each frequency band from 50 Hz to 10 kHz. An estimate of the weighted standard deviation $(10\log_{10}e)\sigma_T/T$ was also calculated for each frequency band. It should be noted that the estimates of standard deviation should not vary with the number of times the test is repeated, although these estimates would be less reliable if fewer repetitions were made.

An estimate of the standard deviation σ_{SRI} was then calculated. As a target, a standard deviation for SRI of about 0.2 dB in all frequency bands was desirable. To achieve this repeatability, the time over which SLD is measured had to be more than one minute, and the number of decays used to measure RT also had to be more than ten. The effects of such changes were studied in the 100 Hz band — (one of the worst in terms of repeatability). For both RT and SLD, the standard deviation was approximately proportional to $1/n^{0.7}$ where n is either the measurement time for SLD or the number of decays for RT. The standard deviation should vary as $1/n^{0.5}$ for a random variable.

The outcome of this study indicated that the SLD should be measured over two minutes. The number of decays required in each frequency band for the measurement of RT was then estimated, assuming that the standard deviation was proportional to $1/n^{0.7}$ in all frequency bands (82 decays were needed between the 50 Hz and 160 Hz frequency bands, 22 decays were needed between 200 Hz and 800 Hz, and 10 decays were needed between 1 kHz and 10 kHz). Using these measurement conditions, the standard deviation σ_{SRI} only exceeded 0.2 dB at 63 Hz but the British Standard method for measurement of sound insulation recommends that SRI should be calculated only for the frequency range 100-3150 Hz. Thus, over the standard frequency range, the repeatability will be better than that recommended in British Standard BS2750[13].

5. PROVING OF THE REVERBERATION ROOM

5.1 Introduction

The receive room of the Transmission Suite was designed so that it could be used as a 200 m^3 ISO-Standard reverberation room[14]. Reverberation rooms are used to measure the acoustic absorption of materials so that their effect on the acoustic of a room can be calculated[15]. They can also be used to measure the sound power emitted by machinery or equipment[16].

The ISO-Standard recommends a suitable reverberation room shape and volume, and gives a maximum figure for the absorption of the walls of the room. The recommended sample area is between ten and twelve square metres. The Standard also advises on :

a) The required repeatability of results (i.e. the level of agreement between results which are obtained in the same reverberation room for the same sample using the same method and equipment and the same test engineer over a short period of time).

b) The required reproducibility of results (i.e. the level of agreement between results for the same sample using the same method agree for different reverberation rooms or equipment or different test engineers at different times).

c) The required diffusion in the reverberation room. A perfectly diffuse field in a room would give the same sound pressure level (s.p.l.) at all points in the room. The value of absorption coefficient obtained for a sample will not be accurate if the sound field in the reverberation room is not sufficiently diffuse.

The Eyring formula for reverberation time[17] is

$$T = 0.161V/(MV - S\log_e(1 - \alpha)) \qquad (5)$$

where

T = reverberation time (s),
V = room volume (m^3),
S = room surface area (m^2),
M = air absorption term (= 4m where m is in nepers/m),
α = mean absorption coefficient.

In the empty reverberation room,

$$\alpha = \alpha_{\mathrm{walls}} = \text{mean absorption coefficient of walls.}$$

In the treated reverberation room, if the sample does not obscure the walls,

$$\alpha = (A\alpha_{\mathrm{sample}} + S\alpha_{\mathrm{walls}})/(A + S)$$

where

α_{sample} = mean absorption coefficient of sample, area A.

If the sample obscures the walls,

$$\alpha = (A\alpha_{\mathrm{sample}} + [S - A]\alpha_{\mathrm{walls}})/S$$

Hence the absorption coefficient of the test sample can be calculated by knowing the reverberation time in the receive room with and without the test sample.

5.2 Repeatability of measurements

The repeatability of measurements of absorption coefficients made in the receive room over a short period of time has to be known. This will depend upon the number of decays used for measurement of reverberation time, the reverberation time, and the accuracy to which temperature and humidity can be measured when calculating the air absorption in the room. From Equation 5, the variance in absorption coefficient σ_a^2 is given by

$$\sigma_a^2 = 2(V/A)^2(0.026\sigma_T^2/T^4 + \sigma_M^2) \qquad (6)$$

where

σ_T^2 = variance in reverberation time T,
σ_M^2 = variance in air absorption M.

The standard deviation was calculated for ten measurements of reverberation time made over a short period of time in the receive room using a known sample of modular absorber boxes. Ten decays were used in each frequency band, and the standard deviations of the reverberation time in each frequency band σ_T was calculated. The standard deviation of the air absorption term, σ_M was calculated from tables of air absorption, knowing that humidity can be measured at least to the nearest 4% and temperature to the nearest 0.5 °C using the present equipment at Research Department.

The standard deviations of the absorption coefficients were then calculated from Equation 6. An acceptable value for the standard deviation of the absorption coefficient would be approximately 0.04 in all frequency bands. To achieve this repeatability, more than ten decays were needed in some frequency bands, so the effect of the number of decays used on the standard deviation was studied in the 100 Hz frequency band, which had one of the worst standard deviations. The reverberation time was measured ten times using either 1 decay, 10 decays or 82 decays. The standard deviation varied approximately as $1/n^{0.7}$, perhaps because the rotating microphone boom does not fully explore the whole space of the room.

The required numbers of decays in each frequency band (to give a standard deviation for the absorption coefficient of approximately 0.04) were then estimated assuming the standard deviation of reverberation time varies in the same way in all frequency bands. This resulted in more decays being recommended than the minimum number recommended in the British Standard, and the resulting repeatability is better than that required by the Standard.

5.3 Investigation of diffusion

A state of perfect diffusion in a room is defined as an equal probability of a sound wave moving in any direction. This is an abstraction which is impossible to quantify. In practice, various measures have been proposed, one of which consists of measuring the average sound level at a large number of points throughout the room for a point sound source. But the British Standard does not recommend this and the results would be difficult to display and interpret.

The British Standard recommends that the absorption coefficients of a sample of mineral wool should be measured with different numbers of diffusing sheets hung freely in the room. The diffusers ideally should not be absorbent, and 2 mm thick acrylic sheet was used in this case. The sheets (area 2.2 m^2 each side) were added three at a time, in random orientations, and the RT with and without the mineral wool was measured each time. The total surface area of twelve diffusers is about 25% of the surface area of the room.

The results are shown in Fig. 18. As more diffusers are added, the measured absorption coefficient characteristic tends to a constant value and at least nine are needed. The apparent absorption increases as the field becomes more diffuse because the statistical (random incidence) absorption coefficient is greater than that for a finite number of angles of incidence[18].

In the BBC Research Department old reverberation room, it has been shown[19] that diffusion is not needed provided the test sample is spread out over several room surfaces (walls). However the old reverberation room has non-parallel walls which aid diffusion, unlike the new one. Also, it is not always possible to spread the sample out, the ISO-Standard recommends that it should not be spread out, and so additional diffusing elements will always be needed in the receive room of the Transmission Suite.

The apparent absorption coefficient of the diffusers alone is shown in Fig. 19. It does not vary much with the number present. They do not have a great effect on the mean absorption of the receive room walls (calculated assuming the diffusers are not present in the receive room) as shown in Fig. 20, but adding more slightly increases the absorption. The acrylic sheets are effective diffusers and are very reflective, as expected. In fact, there will be a small discrepancy caused by assuming that the diffusers are not present when calculating the effective absorption coefficient of the bare receive room walls. This discrepancy is unavoidable and will give a small error when allowing for the area of room surface covered by the sample. However, other similar errors will

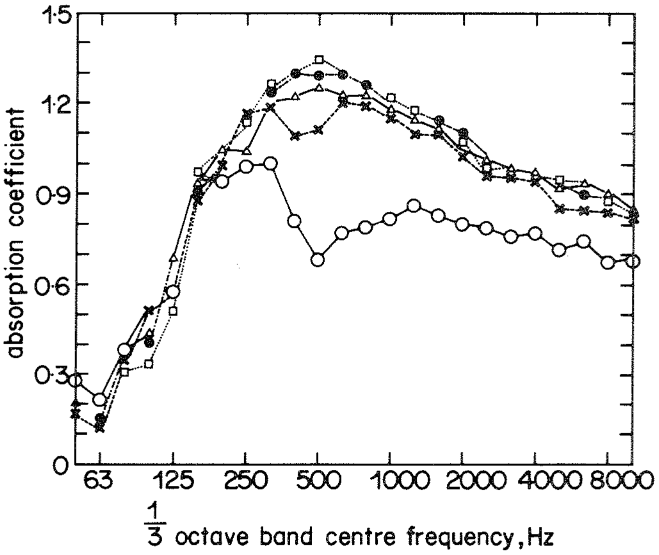


Fig. 18 - The effect of the number of diffusers used in the receive room on the measured absorption coefficient of 10.8 m^2 of mineral wool.

○——○ (a) no diffusers
×------× (b) 3 diffusers
△——△ (c) 6 diffusers
●– – –● (d) 9 diffusers
□·········□ (e) 12 diffusers

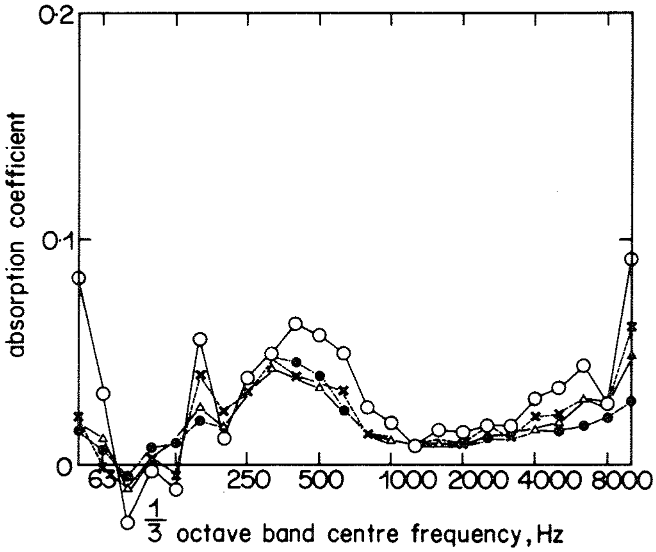


Fig. 19 - The effect of the number (i.e. the area) of diffusers used in the receive room on their measured absorption coefficient.

○——○ (a) 3 diffusers
×------× (b) 6 diffusers
△——△ (c) 9 diffusers
●——● (d) 12 diffusers

occur if the absorption of the 'empty' room is not the same for all room surfaces. This situation already occurs as the receive room floor, ceiling, walls, door and the test partition will all have different absorption coefficients. These errors are all very small because they are errors in second-order correction terms.

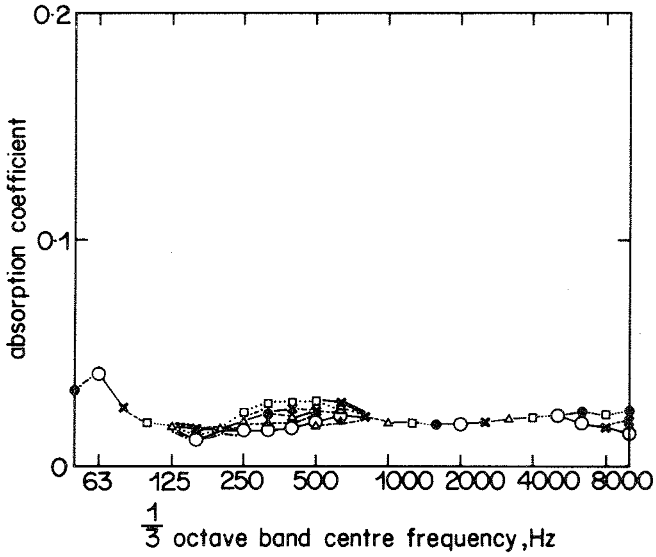


Fig. 20 - The effect of the number of diffusers used in the otherwise untreated receive room on the effective absorption coefficient of its walls.

○——○ (a) no diffusers
×------× (b) 3 diffusers
△——△ (c) 6 diffusers
●------● (d) 9 diffusers
□·········□ (e) 12 diffusers

6. CONCLUSIONS

The airborne sound insulation of walls with mean sound reduction indices less than 65 dB can be measured in the Transmission Suite, now that a permanent flexible acoustic seal has been fitted in the cavity between source and receive room stub walls. Greater sound reduction indices could be measured if some of the leaves of a multi-leaf wall were built in the opening in the source room. The doors and building walls isolate sufficiently so that they will not affect measurements up to a mean sound reduction index of approximately 100 dB.

The leaves of any test wall built into the opening in the receive room should be isolated from the receive room walls. The same comment applies for any walls which are built on the receive room floor.

Workmanship will always be very important when building partitions for high sound insulation. This is relevant in both the laboratory and in studio environments. 'Frogs' in bricks should always be upwards and there should be no voids in the mortar. Sealing the top of a brick wall built up to an existing lintel will create special problems, and care should be taken to ensure that the region above the top course is fully packed with mortar and/or heavy flexible sealing compound. Better still a detail should be developed which anticipates settlement cracks without compromise to the sound insulation.

Measurement technique is very important. The source and receive rooms should be acoustically treated so that the reverberation time in both does not exceed two seconds (to comply with the British Standard method for measurement of sound insulation in laboratories). The effects of room treatment on sound reduction index will be small but measurable. Diffusing elements should be used in both rooms, and it is intended that diffusing elements will be fitted in the source room at a later date. The microphones in the source and receive room should be on booms that rotate. A wideband, continuous acoustic source should be used, and the sound pressure levels should be averaged over at least two minutes. A band-limited acoustic source may be used in those frequency bands where receive room background noise is a problem. Swept warble tone should not be used for any laboratory insulation measurements.

The reverberation room in the Transmission Suite has been shown to meet the ISO-Standard for reverberation rooms. Its volume, dimensions and empty wall absorption satisfy the recommendations. Repeatability tests gave the minimum number of decays required in each frequency band for absorption coefficient measurements. Temperature and humidity should be measured as accurately as possible so that allowance for air absorption can be made — at least to within ±2% Relative Humidity and ±0.25 °C.

Diffusers must be used in the reverberation room. To comply with the ISO-Standard, the test sample should be laid out as one block. This will give absorption coefficients for samples which are directly comparable with those measured for samples in other ISO-Standard reverberation rooms. The reverberation time in the reverberation room without the sample should be as high as possible. Other absorbers should not be left in the room and, if the test wall is highly absorbent, it should be covered with non-absorbing steel panels. Between ten and twelve square metres of sample should be used to comply with the ISO-Standard.

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